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THEORETICAL ASPECTS OF PHOTOVOLTAIC CELL OPERATION

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1. INTRODUCTION

The photovoltaic effect was first discovered in a liquid solution in 1839. In 1876, the discovery of the photovoltaic effect in solid material followed when selenium was used to convert about 1 percent of sunlight into electricity. The development of semiconductor technology in the early 1940s contributed to new advances in the photovoltaic field. The feasibility of a photovoltaic device made of pure silicon was demonstrated by Bell Telephone Laboratories in the United States in 1941. However, the first practical solar cell was not introduced until 1953 in response to the needs of the space program. These first solar photovoltaic cells were made of single crystal silicon and showed about 6 percent efficiency. Single-crystal silicon is the most commonly used material in the manufacture of solar cells today. The present high costs associated with the manufacture of single-crystal silicon has prompted intensified research on polycrystalline and amorphous silicon cells to reduce the cells' cost. This cost reduction can be accomplished by using lower purity silicon material, less expensive refining processes and less silicon for each cell. Also, during the last few years, thin film techniques and concentrators have been used to achieve this goal. In addition to silicon-based materials, non-silicon-based materials have been used for photovoltaic cells. This group includes cadmium sulfide, cuprous oxides and gallium arsenide, as well as other more complex compounds [1]. These new techniques and manufacturing

Technologies demand theoretical and experimental studies of various effects taking place during photocurrent generation in a cell. Thus, understanding the basic aspects of a photovoltaic cell's operation is an essential element of the research and development taking place in the photovoltaic area today.

2. PHOTOVOLTAIC EFFECT

A photovoltaic cell consists of two layers of semiconductor materials, a p-layer and n-layer, put together in a sandwich configuration (see Fig. 1). The sunlight photons having the energy shown by equation (2) $E = hv$ where E = energy of photon, v = frequency of light, h = Planck's constant, E_g= band gap energy of the semiconductor material can free electrons from their covalent bonds in the cell material when striking the photovoltaic cell surface.

Different photovoltaic cell materials have different band gap energies at which electrons are freed. For silicon, the band gap energy value is approximately 1.1 eV at 300 K so that light with a wavelength shorter than 1.13 um frees electrons from their covalent bonds. For gallium arsenide, the E_g = 1.4 eV; other photovoltaic materials have band gap energy from 0.6 to 2.6 eV.

For outer space (AMO), the best photovoltaic material is one with a band gap at 1.6 eV. Because of changes in the solar energy spectrum as sunlight passes through the atmosphere at sea level (AMI), the predicted optimum lies between 1.25 and 1.3 eV.

If an electron is excited across the gap, it leaves a vacancy in the valence band which is referred to as a "hole". An electron near a hole can jump in to fill that vacancy, leaving a new hole at the place that it had occupied, and that vacancy can in turn be filled by another electron, and so on.

In a photovoltaic cell, the current is then actually carried by electrons moving in relays, but it can equally be pictured as a flow of positively charged holes moving in the opposite direction during the exposure of a cell to sunlight.

FIGURE 1. P=N junction photovoltaic cell. Selection-pair bond which binds the crystal.

Firmly together. Silicon has four valence electrons, all of which are part of a covalent bond.

The free electrons are the majority carriers in the n-region while the holes are in the p-region. The power of majority carriers, in general, is determined by dopant concentration and is not very sensitive to either thermal or light excitation. However, the number of minority carriers —holes in the n-region and electrons in the p-region — is very sensitive to both thermal and light excitation, and this sensitivity has strong effects on the operation of a solar cell.

The flow of thermally generated minority carriers in a solar cell in darkness is called a "dark drift current." This current is opposite in direction to the photocurrent and it tends to short the device. The dark drift current, or as it is sometimes called the saturation current, is balanced by an opposing flow of charge carriers across the junction — a "back diffusion" of majority carriers (electrons crossing from n-region to p-region, and holes crossing from p-region to n-region), flowing against the electrostatic potential established by the junction. These two opposing currents are equal in magnitude and as a result, a p-n junction in the dark produces no net current. When sunlight falls on a p-n junction photovoltaic cell while it is short-circuited, the magnitude of the electrostatic potential remains basically the same as it was in darkness, although additional minority carriers are formed by photons absorbed in both n-regions and p-regions and are swept across the junction.

The flow of these minority carriers is in the same direction as the dark drift current, and is a net current flow called the photogenerated short-circuit current. The photogenerated current in an external load RL (see Pill 1) is proportional to the intensity of sunlight. The same photovoltaic cell in sunlight, but under an open-circuit condition, cannot develop a net current flow, instead, the cell achieves an equal internal flow of majority and minority carriers.

Carriers cross the junction by reducing the electrostatic potential from its original value. This decrease in barrier potential causes a voltage of the same magnitude across the open-circuit terminals of the cell, which is called the open-circuit voltage V.

PHOTOVOLTAIC CELL OPERATION

When an external load is connected across a photovoltaic cell subjected to sunlight exposure, electric current will flow and useful power will be delivered. The voltage across the cell will be reduced from the open-circuit value, hence the cell net current will be the difference between the photo-generated current J, and the cell dark current I.

Figure 2 shows the J-V characteristic for a photovoltaic cell with a silicon crystal with added phosphorus dopant, which is called n-type (negative) silicon, and with added boron, it is called p-type (positive) silicon. This is a line which divides n-type from p-type silicon and establishes the position of the electric potential barrier essential to the operation of a photovoltaic cell.

FIGURE 2. J-V characteristics for a photovoltaic cell under variable load conditions. The shift in the J-V curve occurs when the load is varied. This curve is basically the diode J-V curve shifted down the current axis by the amount of the photocurrent. In the forward bias condition, the current increases exponentially with applied voltages. Using the above relationship, the limiting behavior of any photovoltaic cell can be predicted by determining J, and J values. Experimentally, the dark current value can be obtained by applying a large negative voltage across the junction.

When a photovoltaic cell operates under short circuit conditions, the net current through the cell can be determined through the following equation:

Illumination current - Dark current = Voltage across load

In the case of an open circuit operation, R = 0 and V = Voc, where Voc = VI + I). Power output can be expressed as equal to IV.

For

For each photovoltaic cell at a given illumination intensity, there will be a point where maximum power is delivered to the load and the cell operates at or near this point. The condition for maximum power is essential. The photovoltaic cell maximum power is defined as: Pmax = Vmp * Imp. The voltage Vmp at maximum power output is related to the open circuit voltage Uc by the following expression: Woe exp Sgt x (GgBP + a) = exp 259 om and R, we. This equation is relevant where A is the area of the photovoltaic cell. Another parameter related to open circuit voltage is called the voltage factor (VF) and is defined as the ratio of Vc to the band gap energy Eg.

Maximum power which can be delivered by a photovoltaic cell is represented by the largest rectangle which can be contained under the illuminated J-V curve of the cell (see Fig. 2). The voltage Uap and the current Jno defining this rectangle describes another parameter which is called a fill factor (FF). The fill factor accounts for all the effects acting on the shape of the dark current curve.

The maximum power obtained from a pn junction photovoltaic cell depends upon the Vc, Eg and FF values. Finally, the conversion efficiency of a photovoltaic cell is defined as the ratio of cell electrical power output to solar power input. Thus, the theoretical conversion efficiency of the photovoltaic cell at the maximum power point is equal to: Vc x Eg x FF x Io / Input Power.

Because of the low power density of sunlight and the limited conversion efficiencies, today's photovoltaic cells can generate only up to 250 watts per square meter. Figure 3 shows the theoretical conversion efficiencies of various photovoltaic cells.

PARAMETERS AFFECTING CELL EFFICIENCY

4.1 Open Circuit Voltage

Open circuit voltage is one of the parameters...

The text contains several errors and unclear sentences. The corrected text could be as follows:

The efficiency of a photovoltaic cell is affected by its high value, which is desirable. At room temperature, and with a value greater than 3, it can be noted that the voltage can be maximized by minimizing this value. Therefore, it is important to consider the values affecting Ip. For a monocrystal, it can be shown that the minority carrier concentration values in n and p layers, and the majority carrier diffusion length in n and p layers respectively, play a significant role.

The diffusion coefficients of minority carriers in n and p layers and the minority carrier lifetimes in n and p layers are also important. In commercially processed cells, a short diffusion length is observed since a large number of generated carriers recombine on the back surface of a cell. The mobilities of minority carriers in the n and p layers respectively are also factors to consider. For pn junction with a<c<p, the value of this will be significant.

With a large impurity concentration of the order of 10^19/cm^3, the minority carrier's lifetime is 164 µsec, and this results in a very large minority carrier diffusion length. The minority lifetime in the base layer, which depends on the purity and perfection of the base material, is one of the most important parameters affecting the cell efficiency.

As a result, it can be shown that for a silicon monocrystal cell of p-n type, the value of the open circuit voltage at room temperature is: 0.062 exp (39 t), 0.0575 x log {x x (0.062 exp (28 x Yoo)} 5 x Log {a x L pe}. The equation (19) shows that the larger the band gap, the larger the open circuit voltage. For a given band gap material, the resistivity of the material should be low; the carriers should have low mobility and high minority carrier lifetimes. Furthermore, the net current should be large for a high Vic.

In a polycrystalline silicon cell, the voltage depends on the grain size; the larger the grain size, the larger the open circuit voltage, as shown in Figure 4. The grain size can vary from 1 µm to several millimeters.

Even centimeters.

Current, smavem?

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Voltage, Volts

FIGURE 4. Voc dependence on the grain size for polycrystalline and single crystal silicon [3].

4.2 Short Circuit Current

The short circuit current can be expressed by the following relationship (20) where L is the light absorption coefficient.

4.3. Shunt and Series Resistance

Photovoltaic cells may have a shunt resistance Ry, as a result of manufacturing, and may have a series resistance RS, due in large part to the resistance to conduction in the thin diffused layer on the top of the cell. The internal voltage drop in a cell can usually be minimized by the proper design of the metalization, resulting in the conductivity of the material to be such that Rs is often assumed to be equal to zero.

Figure 5 shows the equivalent circuit diagram of a p-n junction without Ry and Rs, and Figure 6 shows the equivalent circuit of a photovoltaic cell with Ry and Rs. It can be shown that as a result of the series resistance and the shunt resistance, the J-V relationship takes the following form:

ap-3 vor any Rea ee $x werny = ane +n en

FIGURE 5. Equivalent circuit cell without Ry and Rs.

FIGURE 6. Equivalent circuit diagram for a p-n junction photovoltaic cell with Ry and Rs.

A= area of photovoltaic cell. Increasing values of Rs and Ry makes the fill factor decrease in value and for high efficiency of a photovoltaic cell, both Ry and Rs should be small.

4.4 Current and Voltage Losses

The most effective crystalline silicon laboratory cells use a p-n homojunction and convert up to 19 percent of the energy in incident sunlight into electricity at 20°C and AM0. In theory, silicon p-n junction photovoltaic cells can convert a maximum of about 22 percent of energy in AM0 sunlight into electricity. However, 73 percent of the energy in sunlight is lost due to factors intrinsic to the cell itself.

Resistance losses. Resistance losses lower a cell's output voltage and enhance the chance of

Recombination of charges reduces the net electric current. Resistance losses primarily occur in the bulk of the base material, in the top surface layer, and at the interface between the cell and the electric contacts leading to an external circuit.

Recombination of charges results from the intrinsic resistance in the cell and leads to current and voltage losses. When this happens, charge mobilities are reduced and the likelihood of recombination increases. This is caused by empty bonds from impurities or defects (fractures), which can capture free electrons or holes. This indirect recombination is dominant.

The surface of a cell can be the site of much recombination. In polycrystalline silicon cells, the recombination per unit volume is inversely proportional to the grain size and depends on the diffusion potential. This causes the minority carrier lifetime to decrease with grain size.

Low and high temperature losses occur. Low-temperature losses occur as temperature falls, since thermal energy is less able to free charge carriers from either dopant atoms or intrinsic silicon. The mobility of charge carriers drops and dopants behave as if they were normal silicon atoms. When the temperature of a photovoltaic cell rises, the cell conversion efficiency decreases as illustrated in Figure 7. This decrease occurs because the additional thermal energy increases the thermally generated dark drift current.

Reflection losses of sunlight that strike photovoltaic cells can be reduced below 5 percent by applying anti-reflective coating or texturing the surface. Normal, untreated silicon reflects from 36 to 70 percent of sunlight which strikes it depending on the wavelength as shown in Figure 8.

Absorption of photons by the cell material is another factor.

"Influencing the coal merit method, the intensity of photons at depth x can be presented by the following equation: $I = I0 \exp(-\alpha x)$ (22), where:

- $I0$ = intensity of photons at the material surface
- α = absorption coefficient of material.

Refer to figure 58 for additional information.

Section 2: It is clear that electron-hole generation decreases exponentially with distance into the semiconductor. The absorption effect for Silicon exposed to AM0 and AM1 sunlight is shown in Figure 9. The excess of energy which is not absorbed by the material is lost as heat. In the case of silicon, all photons with wavelength 1.13µm are lost. These losses can be in the range of 30 percent. Figure 10 shows the variation of the absorption coefficient with incident sunlight energy for various photovoltaic cells.

Section 5: Conclusions

The various parameters discussed above have a significant impact on photovoltaic cell operation and performance. These parameters could be divided into mechanical, electrical, optical, and thermal ones. The role of some of them during the cell's operation is already well known, others are still being studied. Thanks to extensive experimental research and theoretical studies, significant progress has been made in better understanding the various theoretical aspects of a photovoltaic cell's operation. Because of this, and the use of a new generation of cells and improved production technology, an increase in the efficiency of crystalline silicon cells from 14 percent to 19 percent occurred. This was accompanied by a decrease in cost by more than half during the last decade of photovoltaic generated electricity, from about $20 per peak watt in 1976 to $7-$10 per peak watt today. In the same period, the worldwide production of..."

Photovoltaic cells increased from 0.45 MW to over 25 MW, signifying remarkable market penetration and the large potential use of photovoltaic cells.

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